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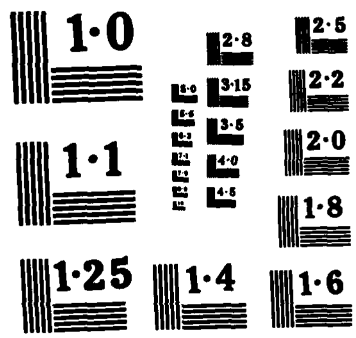
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Cognitive Science Program

FORCE AND TIMING COMPONENTS OF THE MOTOR PROGRAM

by

Richard B. Ivry

University of Oregon

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Three experiments assess the effects of variations of force and time on response latency on both simple and choice reaction time. The first two experiments demonstrate that, while latency does not vary as a function of force, increasing timing demands by requiring that a response be maintained led to increases in reaction time. These results led to the development of a model of motor programming in which force and timing are dissociated as separate components. However, the data also indicated that the force component may be further analyzed into two subcomponents--force activation and force

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deactivation. The model predicts that the latter subcomponent may be programmed on-line provided sufficient time elapses between the implementation of the two subcomponents. The results of Experiment 3 support this prediction and further validate the proposed model. Keywords:

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FORCE AND TIMING COMPONENTS OF THE MOTOR PROGRAM

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Abstract

Three experiments assess the effects of variations of force and time on response latency On both simple and choice reaction time. The first two experiments demonstrate that, while latency does not vary as a function of force, increasing timing demands by requiring that a response be maintained led to increases in reaction time. These results led to the development of a model of motor programming in which force and timing are dissociated as separate components. However, the data also indicated that the force component may be further analyzed into two subcomponents--force activation and force deactivation. The model predicts that the latter subcomponent may be programmed on-line provided sufficient time elapses between the implementation of the two subcomponents. The results of Experiment 3 support this prediction and further validate the proposed model.

Force and Timing Components of the Motor Program

Richard B. Ivry

Introduction

A basic assumption underlying much research on movement control is the notion that an entire movement may be centrally represented. This assumption was provided with a structural base by the conception of a motor program (Keele, 1968; 1981; Schmidt, 1983). The program is hypothesized to embody both the goal of the movement and the different components that are required to attain that goal. While the end-goal of movement has not been difficult to experimentally manipulate, the task of identifying the different program components has proved to be much more elusive. It is obvious at the most superficial level that movement (both isometric and isotonic) entails a change in the state of the target muscles for a variable period of time. However, there are a number of different ways in which these changes can be effected and thus it has remained unclear how a central control system governs movement (see Stein, 1982 for a review of this problem).

One paradigm which has been widely employed in the endeavor to identify the components of the motor program has been to infer movement complexity by looking at differences in response latency (e.g. Klapp, Wyatt, and Lingo, 1974; Rosenbaum, 1980). This paradigm has its roots in Henry and Rogers' (1960) memory drum theory. The theory proposes that more complex movements entail larger programs and thus, more preparation time for the person to access the information required for the coordination of the neural signals needed to trigger the movement.

Considerably less unanimity is found in the literature when trying to identify what is meant by "complexity". Rosenbaum and his associates (1980; Rosenbaum, Inhoff, and Gordon, 1984) have shown that latencies increase as a function of hand selection, direction of movement, and to a lesser degree, extent of movement. As combinations of these factors have to be specified during the preparation period, latencies are further slowed. Thus, they have approached the question of complexity by varying the amount of uncertainty. Other researchers (Klapp, Anderson, and Berrian, 1973; Sternberg, Monsell, Knoll, and Wright, 1978) have demonstrated that in the linguistic domain, number of syllables can serve as a measure of complexity. While studies such as these are useful in showing that reaction times may increase as more components of a movement need to be specified, they still provide only a general description of the constituents of a motor program.

A more detailed method of looking at the complexity effect is encompassed in experiments in which the basic movement remains unchanged, but the parameterization of single components is varied. For instance, Baba and Marteniuk (1983) used a modified simple reaction time paradigm (go versus no-go) to test whether varying force or varying duration led to increases in response latency. They found that for simple movements involving flexion of the elbow, RT did not increase as a function of force when duration was held constant. However, RT did increase significantly as movement duration was increased with force held constant. Klapp et al (1974) have found similar results in choice reaction time experiments. Both researchers (Baba and Marteniuk, 1983; Klapp and Erwin 1976) have speculated that the increase in latency as a function of increased movement duration may be related to the generation of more complex timing circuits. However, other studies in which force and time were not independently controlled or varied have provided less clear results. For instance, Lagasse and Hays (1973) and Glencross (1972) found that RT did not differ when subjects had to make either long or short movements. While movement time was greater for the long movements, neither experimenter obtained any measure of force. Thus, it is not possible to determine the variables which their subjects manipulated to produce the different movements.

The variables which have been investigated in these studies seem especially pertinent when considering broader questions of motor control. Specifically, it has been hypothesized by a number of researchers that force and timing may be independently controlled. For instance, both Freund and Bundingen (1978) with humans and Ghez (1979) with cats have found that in making rapid movements of varying force, the duration of the initial EMG burst appears to be invariant. They point out that such an organization of the system, in which certain timing aspects are invariant, greatly reduces control problems in that the subject only needs to select the appropriate force to comply with the demands of the task. Of course their research is looking at the movement itself and thus it is a few levels removed from the central control system. However, recordings from either single motor units (Tanji and Kato, 1973) or cortical cells (Smith, Hepp-Reymond, and Wyss, 1975) have also provided evidence for separate control of force and timing. Both studies have shown that while most neural units appear to fire in a direct relationship with the force required, there are some units whose firing frequency is not correlated with force, but remain constant throughout the duration of the movement. These units may be coding timing information.

The experiments to be reported here constitute an attempt to further clarify the effects of variations in force and time on response latencies. In Experiment 1 subjects were required to vary force while keeping response duration fairly constant whereas in Experiment 2, force was held constant and duration was manipulated. All movements were performed isometrically by pressing against a strain gauge. This allowed for greater experimental control in that neither force nor time are confounded with extent. The combined results of these two experiments led to the development of a model which specifies some of the components and sub-components of simple movements. Experiment 3 tested a prediction of this model.

All three experiments involve both choice and simple reaction time sessions. While Klapp et al (1974) have employed a similar approach, their motivation was to demonstrate the merits of one approach over the other as a means for assessing motor programming. This has led to long and sometimes tempestuous debate in the literature (e.g. Henry, 1980; Marteniuk and MacKenzie, 1981; Klapp, 1981). As the present experiments will show, this may be an empty argument and the (unfortunate) consequence of strict adherance to the metaphor of computer programming. In the computer domain, the term "programming" is reserved for the process of constructing the program. However, in the psychological literature, "programming" has generally been used to refer to all of the events preceeding response initiation. As many authors have noted, the initiation process may include distinct phases: One phase must be concerned with program construction, but an additional phase may be necessary for implementing the program, i.e. reading the program out of a holding buffer (Sternberg et al, 1978; Rosenbaum et al, 1984). Since the motor control theorist is concerned with the entire process governing movement, methodologies which allow the researcher to identify the specific processes of each phase should be viewed as an experimental aid and not as an obstacle. Choice and simple RT conditions will be employed as complements in the present experiments since each may illuminate different aspects of the response preparation period.

Experiment 1

Experiment 1 was designed to test whether varying the amount of force required to perform an isometric movement influenced choice or simple reaction time. More specific, does programming a desired force require a constant amount of time, or is it a function of force?

Since movements of greater force entail both the recruitment of more motor units and increases in the firing frequency of these units (e.g. Desmedt, 1983), one possibility would be that movements of greater force will take longer to prepare. The notion here is that the recruitment of a greater quantity of motor units involves a more complex program due to the stronger central signal. On the other hand, Ghez and Vicario (1978) have obtained the opposite latency profile in a choice reaction time paradigm with cats. They found that RT decreased with increases in force, although asymptote was approached by their mid-range force levels.

More analogous to the present experiment is the work of Klemmer (1957). In this simple RT experiment, subjects were asked to increase their force output on a strain gauge by a varying amount. Klemmer found no differences in RT as a function of target force level. In fact, after 3600 trials on each force level, the mean RT for the small force condition was 168 ms. and 169 ms. for the large force condition. The short RT's indicate that subjects must have programmed the response in advance of the reaction signal. Since the simple RT phase of the present experiment is a near-replication of Klemmer's study, it is expected that the same resùlts will be obtained. Whether the same results should be expected in the choice RT sessions is less clear. Assembling the motor program may show differences that do not appear when the measure is taken of the time needed to execute the program.

Method

Apparatus:

A response key was mounted on top of a Grass strain gauge (Model FT10D). The strain gauge sent a pressure-dependent electrical signal to an amplifier which then relayed the signal on to an analogue-to-digital (A to D) converter located in an Apple II microcomputer.

All displays were controlled by the computer and all response measures were collected and recorded by the computer. A minimum displacement criterion to indicate movement onset was set at 1.1 Newtons (N). Due to gravitational force, the typical person's index finger displaces 0.6 N of force simply by resting on the key. Thus the latency was recorded after the subject had generated a force of 0.5 N. Measurements were also obtained for peak force, the time at which peak force was reached, and the duration of the press (recorded at the time the pressure iovment are not both preprogrammed), as has been suggested by some authors (e.g. Desmedt, 1983; Meink, Benecke, Meyer, Hohne, and Conrad, 1984), a different pattern of results may emerge when a greater range of movement durations is tested. Klapp and Erwin (1976) did test a wider range of durations in a lever moving task and found that choice RT's were consistently slower for movements of long duration. However, it can be inferred from their methodology that the initial velocity profiles were quite different between the various duration conditions. The present experiment was designed to avoid this confound.

Method

Apparatus: The apparatus was the same as in Experiment 1.

Subjects: Ten youg adults were selected from the Cognitive Laboratory Subject Pool at the University of Oregon. Three of the subjects had participated in Experiment 1 while the remaining seven were new to this series of experiments. As before, all were right handed with normal or corrected to normal vision and hearing. The S's were paid $6.

Procedure: The procedure in both simple and choice RT conditions was essentially unchanged (see Figure 1). However, the movement requirements were different. Subjects were asked on all responses to generate a force of 7.5 N. This corresponded were given extensive practice (Experiment II). It is unclear, however, if providing subjects with a lot of practice is the best method for assessing motor programming differences. Practice in such simple tasks may allow for the establishment of programs which bypass the normal processing paths.

There are other methodological and theoretical reasons to question the generality of Klapp's results. First, both Kerr (1979) and Klapp and Greim (1981) have demonstrated that the differences due to variation in timing disappear under certain feedback conditions. Secondly, in their original experiment, Klapp *et al* (1974) required subjects to begin each trial by depressing the morse key. Thus, their movements actually involved two phases-- the subjects had to lift their finger up before reversing the movement to make their response. This adds an unwanted degree of complexity to the movement.

More important for our present purpose is the fact that the "long" duration movements in both the Klapp studies and the experiment of Baba and Marteniuk (1983) are actually quite short. In the former's studies, the "long" response is only 300 msec. whereas the latter researchers considered 220 msec. movement durations as long. It is quite probable that the entire movements in these experiments from start to finish was programmed prior to movement onset. Thus, the latency profiles may only reflect quantitative programming differences. That is, all of these movements are ballistic in nature and only vary slightly in the speed in which they are executed. If longer duration movements are qualitatively different (i.e. the onset and offset of the

Experiment 2

Experiment 2 was designed to look at the other part of force-timing models of motor control-- namely, is response latency influenced by the duration of the intended movement. All of the responses were performed isometrically on a strain gauge and the force required in the different timing conditions was held constant. However, the subjects were required to maintain their responses for a variable period of time. This method allowed us to study the influence of timing variation when all other aspects of the movement are held constant.

Similar manipulations have been performed in the past. Baba and Marteniuk (1983) held torque constant in a simple RT experiment with isotonic movements by allowing longer duration movements for heavier weights. They found that subjects took more time to initiate the longer movements. However, since extent was the same in all of their conditions, it can be inferred that the subjects performed the movements more slowly in the long duration movement condition. Another design has repeatedly been employed by Klapp and his associates (Klapp et al, 1974; Klapp and Rodriquez, 1982; Klapp and Greim, 1981). In those experiments, the subject was required to press a morse key for either a short (100 msec.) or long (300 msec.) interval. In the original experiment (Klapp et al, 1974, Experiment 1), response latencies under both simple and choice RT conditions were significantly faster for the short responses. Those differences disappeared in the simple RT condition when subjects mean times to reach peak force in Experiment 1 were all less than 115 ms., it can be concluded that the subjects had selected an appropriate force output level before initiating their responses. The lack of differences in latency profiles implies that the selection of an appropriate force level requires a constant amount of time. Since the data clearly show that the responses have been prepared in advance of the reaction signal in the simple RT condition, then it can also be inferred that the time required to generate the neural signals to the muscles is also invariant across different force levels.

identification or response selection.

These findings replicate and extend the observations of Klemmer (1957) who obtained similar results in a simple RT experiment using two force levels.

The failure to find any differences in latency in the choice RT condition may appear to contradict the results of Ghez and Vicario (1978). They found that the reaction times for cats decreased with increases in force. Besides the differences in species tested and the question of whether the term "choice reaction" time can adequately be appplied to cats, a more concrete explanation can account for the ambiguity. The task in their experiment was to generate an appropriate amount of force to return a feeder to a center position. Deflection of the feeder served as the stimulus and the speed of deflection indicated to the animal the amount of force required. As Ghez and Vicario (1978; also Ghez, 1979) note, stronger stimuli are generally responded to faster, and thus their target forces are confounded with stimulus intensity.

The results obtained in Experiment 1 and the supplementary experiment with isometric contractions are also consistent with latency data recorded during isotonic movements in which force is varied (Glencross, 1972; Lagasse and Hays, 1973; Baba and Marteniuk, 1983).

What inferences can be drawn from these results in view of a theory of motor control which emphasizes that force and timing must be centrally programmed for ballistic movements? Since the and Target Force did not approach significance, $F(2,14)<1.0$.

Unfortunately, the wider criterion ranges did not greatly reduce the error rates. The overall error rate in the choice RT condition was 37.4% and 34.0% in the simple RT condition. As in Experiment 1, most of the errors were due to subjects producing the wrong maximum force and the error rates tended to increase for the higher target forces. Since the subjects were slowest and made the fewest errors in the same conditions (light contractions in both the simple and choice RT conditions), an explanation based on a trade-off between speed and accuracy may be valid. However, as in Experiment 1, the error profiles were consistent across subjects, yet the latency profiles were quite dissimilar.

Discussion

Taken together, Experiment 1 and the supplementary experiment demonstrate that varying the intensity of an isometric contraction does not influence the time required to initiate the response. This pattern of results is observed in both simple and choice reaction time situations and across two different ranges of target forces. As demonstrated by the significantly longer RT's in the choice condition, different components of the response preparation period are being measured in the two RT conditions. That is, the long RT's in the choice condition reflect additional processing time. It can not be determined whether this additional time is required for stimulus

Supplementary Experiment: As noted above, the interaction between RT mode and Target Force approached significance. To test for the possibility that this interaction may have been obscured by the high variability both between and within subjects, a slightly modified supplementary experiment was conducted with eight new subjects.

This supplementary experiment was designed to be a replication of Experiment 1. A few modifications were adopted to test whether the same results would be obtained in slightly different conditions. Three force levels again served as response targets in both simple and choice RT conditions. However, lighter springs were placed in the strain gauge. This created a new range of target forces of approximately half the values as had been used in Experiment 1. (2) In addition, the criterion range for determining if a subject had made the correct response was increased to plus or minus 25 arbitrary units in an effort to reduce the high error rates. The range in arbitrary units for light contractions was 35-85, for moderate contractions 85-135, and for strong responses 135-185. Since the minimum displacement criterion corresponded to a value of 25 and the maximum response was 188, the three forces cover almost the entire range of the strain gauge.

The latency data were analyzed in the same manner as that of Experiment 1. The results essentially replicate those of Experiment 1: Response latency did not vary as a function of force, and of greatest interest, the interaction between RT mode

Errors: As noted in the Methods section, preliminary testing showed the task to be rather difficult and this was evident in the high error rates. The overall error rate was 41.4% in the choice RT condition and 33.5% in the simple RT condition. The vast majority of these errors were due to subjects producing a peak force value which was either above or below the criterion force levels. 93.7% of the errors in the simple RT condition were of this type and the analogous figure in the choice RT condition was 67.0%. Most of the remaining errors in the choice RT condition were due to slow starts (latency>600 msec.) and these were evenly distributed among the three different force levels. The same dispersion was not evident for the force errors in that the mean number of errors increased with larger target forces.

This last point leaves open the possibility that a trade-off between speed and accuracy may have artifactually contaminated the response latencies. However, two factors argue against such an interpretation. First, while the errors due to applying the wrong force were extremely similar across the two RT conditions, the fastest responses were for different force targets in the two RT conditions. Secondly, the error profiles were consistent across subjects within each RT condition, yet the latency profiles were dissimilar. In other words, there did not appear to be a correlation between the error patterns and the latencies as would be expected if the subjects were engaging in a trade-off between speed and accuracy.

in force. This indicates that more time is required to make stronger isometric contractions. However, all of the responses were quite rapid as indicated by the overall mean time to peak force of 90.7 msec. and overall mean duration of 213.9 msec. Thus, the responses can all be considered ballistic, with time to peak force being too short for feedback control (e.g. Poulton, 1981), and in this sense, qualitatively similar in terms of the timing demands.

Insert Table 1 about here

The main data of interest are the response latencies. These scores were submitted to a 2 (RT Mode: Simple vs. Choice) X 3 (Target Force: 60,100,140) repeated measures ANOVA. Not suprisingly, the factor, RT Mode, was highly significant, $F(1,9)=203.3$, $p<.001$, demonstrating that subjects were able to prepare at least some aspects of their responses in the simple RT sessions. More interesting, the main effect of Target Force was not significant, $F(2,18)=2.04$, $p>.1$. The interaction between the two main effects approached significance, $F(2,18)=3.33$, $.05<p<.10$. The results of the ANOVA do not support a conclusion that response latency is a function of the force required. In fact, the 20 msec. advantage for the two higher force levels in the choice RT condition is primarily the result of the data from two subjects who were approximately 50 msec. faster on responses to the 100 and 140 force targets then to the 60 force targets.

and 15 catch trials. The order of trials within a session was randomly determined by the computer. All trials on which errors occurred were repeated by being replaced back into the set of remaining trials. Thus, at the end of the experiment, each subject had generated 30 error-free data points for analysis at each of the three force levels in both the simple and choice RT conditions.

The order of conditions for half of the subjects was practice simple RT, test simple RT, practice choice RT, test choice RT, test simple RT, and test choice RT. The other half of the subjects started with practice choice RT and a test choice RT session. This was then followed by practice simple RT, test simple RT, test choice RT, and test simple RT.

A complete experimental session lasted approximately 90 minutes.

Results

Table 1 presents the means and mean standard deviations for response latency, maximum force, response duration, and time to peak force in both RT conditions. As can be seen in the second data column, the subjects' mean maximum force for each target level closely matched the target forces of 60, 100, and 140 in both the choice and simple RT conditions. The third and fourth data columns show that the movements themselves were extremely similar between the two RT conditions. Response duration and time to peak force increase more or less linearly with increases

2000 msec after which a new stimulus appeared to initiate the next trial.

Insert Figure 1 about here

Choice RT Conditon:

The sequence of events for the choice RT sessions are shown in the bottom half of Figure 1. These trials were initiated by an auditory warning tone. After a randomly selected interval of either 750, 1000, or 1250 msec., a number from the set (0, 1, 2, or 4) appeared on the center of the screen. This stimulus would indicate the appropriate response and also served as the reaction signal. The digit 4 was presented on one quarter of the trials and was included to create catch trials. As in the simple RT condition, any responses on catch trials were counted as errors and were followed by the message "False Start" in the feedback period. Following the subject's response, feedback was presented in the same manner as described above. The feedback stayed on for 2000 msec. The feedback was then erased and the next trial began after a 2000 msec. rest period.

Each subject participated in one practice bout for each condition (simple or choice RT) and two test sessions for each condition. The practice sessions consisted of 40 trials-- 10 trials at each force level and 10 catch trials. Each test session was composed of 60 trials-- 15 trials at each force level focus on starting their responses quickly and should anticipate making many errors.

Simple RT Condition:

The sequence of events for simple RT sessions is depicted in the top half of Figure 1. A trial began when one of the stimulus numbers (0, 1, or 2) appeared on the center of the display screen. The number indicated which response the subject was to prepare. Two seconds after the target was presented, a warning tone was generated by the computer. A second tone served as the reaction signal and followed the first tone by a randomly selected interval of either 750, 1000, or 1250 msec. The subjects were instructed to respond as quickly as possible to the second tone. On one quarter of the trials, no second tone was generated. These trials were included to insure that the subjects were responding to the reaction signal and not anticipating. Therefore, in addition to the three error messages cited above, a fourth error message was "False Start" for cases in which a person responded on a catch trial. After the subject had responded (or not responded on a catch trial), the stimulus was replaced by feedback. This included the maximum force attained in arbitrary units, the response duration in milliseconds, and the message, "Trial is Good" if all criteria were met. In the advent of an error, the appropriate error message was displayed with the force and duration values. The feedback remained on for purposes. The values 60, 100, and 140 corresponded to the low, moderate, and high force levels, respectively. The subject was considered to have correctly attained the target force if his or her response was within 20 arbitrary units of the target force. Thus the acceptable range for the three conditions was: 0: 40-80; 1: 80-120; 2: 120-160. If the force generated by the subject in experimental trials was either below or above the tolerance criterion, the trial was counted as an error and the message "Out of Force Range" was displayed during the feedback interval. The option of using a proportional method to determine the tolerance ranges was not used since previous research (Sheridan, 1981; Klapp and Greim, 1981) has shown that RT does not change when amplitude is held constant, but the tolerance level is varied.

In addition, two timing criteria were employed to determine the status of a trial. A trial was counted as an error if either the RT was greater than 600 msec., in which case the message, "Slow Start" appeared or if the reponse duration was longer than 400 msec. in which case the feedback message read "Holding Key Press Too Long". The short latency criterion of 600 msec. was chosen to emphasize speed whereas the 400 msec. duration value was adopted to insure that all of the responses were performed rapidly.

Preliminary testing indicated that, due to the sensitivity of the strain gauge and the various criteria, the task was extremely difficult. However, since the primary interest was on the reaction times, the subjects were informed that they should recrossed the criterion point).

Subjects:

Ten young adults were randomly selected from the Cognitive Laboratory Subject Pool at the University of Oregon. All were right handed with normal or corrected to normal vision and hearing. The subjects were paid $6 for their efforts.

Procedure:

The subject sat in front of the display screen in a quiet, dimly lit room. They placed their right index finger on the response key. By requiring the subjects to place their thumb and other fingers on the response board, and their elbow on a table of the same height, isometric movements were restricted to contractions of the muscles controlling the index finger. (1)

The subjects were familiarized with the apparatus and made a few presses to get a feeling for the different target forces. Three different force levels were used in this experiment. Each force level was paired with a digit which served as the stimulus for that force level. A low target force, 4.5 N, was paired with the digit 0, a moderate target force, 7.5 N was paired with the digit 1, and a high target force, 10.5 N, was indicated by the digit 2. Since the A to D converter recorded force on an arbitrary scale from 0 (no force) to 189 (maximum force), the corresponding arbitrary values for each target force were used in both explaining the experiment to the subjects and for feedback to a score of 100 on the arbitrary scale of the A to D converter. Force scores below 70 and over 130 were counted as incorrect and followed by the error message, "Out of Force Range". The stimulus set (0,1,2) was mapped to the responses in the following manner: The 0 stimulus required that the response duration be between 0 and 400 msec. This range was adopted in an effort to ensure that these responses were entirely ballistic. That is, to meet the task demands, the subjects would have to rapidly make a contraction and then release that contraction in order to negate their force output. The 1 stimulus required that the duration be between 700 and 1300 msec. and the 2 stimulus had a tolerance range that went from 1400 to 2600 msec. Both of these conditions were expected to require qualitatively different movements than the responses to the 0 stimulus. The subjects were required to make a single rapid initial contraction as for the 0 stimulus, but then must maintain that contraction for a variable period of time before release. Following Klapp and Erwin (1976), the tolerance range for the two longer responses were set at plus or minus 30% of the target time. A proportion method was adopted following pilot testing. Any response durations which fell outside the respective boundaries were recorded as errors and were followed by the message, "Out of Duration Range". The criteria from Experiment 1 were used to test for "Slow Starts" (latency > 600 msec.) and "False Starts" (responding to the stimulus 4 in the choice RT condition or when a second tone was not presented in the simple RT condition).

It was not possible to obtain a meaningful measure of time to peak force. This was because a subject might slightly increase their force during the hold period and the time at which the new maximum was acheived would be considered by the program as the time at which peak force was acheived. To insure that the initial contractions across all conditions were similar, the instructions emphasized that responses should be made rapidly. Observations by the experimenter and the comments of the subjects during debriefing confirmed that this mode of responding was used. That is, in the hold conditions, subjects rapidly generated a target force and then maintained that force, rather than making ramped, gradual responses.

As in Experiment 1, 40 practice trials preceded the first test session for each RT condition. Two test sessions of 60 trials in each RT condition produced the data for analysis. The order of sessions was counterbalanced across subjects.

Results

Table 2 presents the means and mean standard deviations for response latency, maximum force, and response duration. As is evident in the second data column, the mean force for each timing level closely matched the target force. It can thus be concluded that the initial movement was the same for all six conditions. The third data column shows that the subjects were, for the most part, successful in meeting the time requirements. Responses to the 0 stimulus were ballistic (mean RT=248.3 msec.). The subjects displayed a tendency to hold responses to the 1 stimulus for a longer time than the target time and an even greater trend to shorten the interval on responses to the 2 stimulus. However, considering the wide tolerance ranges, it appears that sufficiently different timing conditions were acheived.

Insert Table 2 about here

The latency data were tested in a 2 (RT Mode: Simple vs. Choice) X 3 (Target Time: Ballistic, 1000 ms. hold, 2000 ms. hold) repeated measures ANOVA. The main effect, RT Mode, was again highly significant, $F(1,9)=53.92$, $p<.001$. As stated before, this demonstrates some programming took place prior to the reaction signal. The main effect of Target Time approached significance, $F(2,18)=2.88$, $.05<p<.10$, and there was a highly significant interaction between these factors, $F(2,18)=9.87$, $p<.001$. Post-hoc analysis was carried out via the Tukey method (overall $a<.05$). This analysis showed that whereas the ballistic responses (0 stimulus) were significantly faster than the hold responses (1 and 2 stimulus) in the simple RT condition (average difference of 23.8 msec.), no differences were observed between the three levels of target time in the choice RT conditon. In fact, the mean latency score for ballistic responses in the latter condition were in the opposite direction (average of 9.6 msec. slower). Comparing the individual subject data for the ballistic condition with the average of the two hold conditions confirms this interaction. All 10 subjects were faster to respond ballistically in the simple RT condition whereas only 2 were faster in the choice RT condition, 7 were slower, and 1 was the same.

Errors: Although this task was also difficult, varying time proved to be somewhat easier for the subjects. The overall error rate was 26.9% in the choice RT condition and 21.6% in the simple RT condition. Except for the slow starts (latency>600 msec.), the error pattern was the same in both RT conditions. As in Experiment 1, it seems difficult to invoke speed-accuracy hypotheses since the same error pattern would have to explain different latency profiles.

As alluded to above, the slow starts were not evenly distributed among the responses in the choice RT condition. 15.7% of the ballistic responses resulted in this type of error whereas only 9.4% of the 1000 msec. hold or 2000 msec. hold trials were similarly terminated. In light of this abberation, the data from the choice RT sessions were reanalyzed, but the criterion RT time was raised to 900 msec. (Since only 0.9% of the responses in the simple RT condition had latencies greater than 600 msec., a similar analysis was unneccessary for this condition.) This reanalysis showed that the difference in response latencies between the 3 levels of Target Time may have been somewhat obscured by the original, strict criterion. The new mean latencies were 487.9 msec., 467.3 msec., and 471.6 msec. for the ballistic, 1000 msec. and 2000 msec. conditions, respectively. (3) Although this post-hoc analysis must be treated cautiously, it lends further support to the hypothesis that, in the choice RT sessions, subjects were slowest when asked to make ballistic responses.

Discussion

Experiment 2 demonstrates that varying the timing demands of a movement can significantly affect the latency profiles. However, the significant interaction indicates that the effect may be differentially manifested as a function of different RT methodologies.

The results in the simple RT condition are conclusive and concur with previous work of Baba and Marteniuk (1983). Subjects are slower to initiate longer duration responses. The evidence supports the hypothesis that when a response requires the maintenance of a contraction, the motor program is more complex and more time is required to implement it. While the latency difference between the 1000 msec. and 2000 msec. hold conditions was not significant, the direction of the means suggests that real-time increases may be reflected in even longer program read-out time. This conjecture must be considered tentative and will require further testing with a greater range of target times.

Interpretation of the data from the choice RT conditions is less straightforward. While the mean latencies in this condition were not statistically different, the means of the individual subjects showed a consistent reversal between the two RT conditions. That is, the subjects were usually slowest to initiate the ballistic responses in the choice RT sessions. This result is especially puzzling if it is assumed that choice RT's encompass all of the preparation phases contained in simple RT's, plus some additional programming demands. It seems unlikely that the differences in time required to implement the motor program disappear in a choice methodology. This suggests that the additional programming demands in the choice RT condition obscure the latency gain found for ballistic responses in the simple RT situation. The following model shows how this may have occurred.

The structure of the model is sketched in Figure 2. There are two primary stages of response preparation in the model. The first stage, shown below the dotted line, involves three processes which are required to construct the motor program. The second stage, shown above the dotted line, represents those processes which are required for implementing the program. It is assumed that the subcomponents in the construction phase are assembled into a holding buffer. The abstract motor program is then transformed into the actual signals to be relayed to the muscles. Responses in simple RT conditions only involve the top stage of the model since the program can be constructed in advance of the reaction signal. However, in the choice RT conditions, the respondent must work through both stages.

Insert Figure 2 about here

How does the model account for the results of the first two experiments? First, the finding that the subjects were slower in the simple RT condition of Experiment 2 for the 1000 msec. and 2000 msec. responses than for the ballistic responses is explained by the hypothesis that less time is required to implement a program when there is no value assigned to the timing control component. It may be that the buffer holds less information and thus can be read-out more quickly. Another possibility is that the time required to read-out the timing instructions may be a function of the real time demands of the task with shorter responses requiring less time. This possibility is suggested by the nonsignificant increase in latency across RT conditions for the 2000 msec. responses in comparison to the 1000 msec. ones. Secondly, the finding that latencies in the choice RT condition for ballistic responses tend to be slower than for the longer duration responses is also accounted for by the model. The force control component in the buffer is the product of two subcomponents-- setting force activation and setting force deactivation. It is assummed that when the response is of sufficient duration, the instructions for deactivating the force can be set after the response is initiated. Thus the two longer responses in the choice RT condition can be initiated faster since the deactivation subcomponent of the construction stage is by-passed. This is not possible for the ballistic responses since the time interval between activation and deactivation is too short to allow the subject to construct the deactivation phase on-line.

The finding in Experiment 1 that latency did not vary as a function of force is also accounted for by the model. All of the responses in Experiment 1 are qualitatively similar and thus entail the same processing subcomponents and buffer structure. Specifically, the timing parameter is set to 0 for all of the responses since the subjects had to rapidly contract and release their muscles in order to meet the task demands. This requires the subjects to set both the activation and deactivation instructions prior to making their response. Note that the time demands for either of these components is assummed not to depend on the quantitative requirements of the different tasks. Furthermore, the model proposes that when both the activation and deactivation of force output are set, they combine to form a single component in the buffer.

This last assumption leads to a prediction of the model. If the timing requirements are held constant subjects should be slower in a choice RT task when a response involves both force activation and deactivation in comparison to responses which only require programming of force activation. However, the same result should not be evident in a simple RT task since these two subcomponents have been merged into a unitary component in the buffer prior to the reaction signal. Experiment 3 tests this prediction.

Experiment 3

All of the responses in Experiment 3 were ballistic in the sense that the timing demands did not allow the subjects to maintain a contraction. Thus, timing control was held constant by requiring its value to be set to 0 for all of the responses. The number of subcomponents (1 or 2) required for force control was varied by using two different responses. The first type of response was designed to entail only the programming of force activation by having the subjects push maximally on the key press. In such a condition, subjects can clearly feel when the strain gauge has reached a maximum compression point. Thus, deactivation of these movements is externally signalled, and therefore it is assumed that programming the deactivation phase can be by-passed. For the other type of response, the subjects were required to make a key press which was less than maximal. In order to avoid the possibility that these responses would involve accuracy demands which were not involved in the maximal responses, the subjects were allowed to make presses which covered almost the entire range of the strain gauge.

As stated above, the model predicts that response latencies should be faster in the choice RT condition for the maximal condition since the deactivation component can be by-passed whereas no differences should be obtained in the simple RT condition. More specifically, the magnitude of the expected RT difference between the two types of responses can be estimated from Experiment 2. In that experiment, ballistic responses were an average of 23.8 msec. faster than the longer duration responses in the simple RT condition. However, these same responses were an average of 9.3 msec. slower in the choice RT condition. If it is assumed that the gain in latency when there is no timing requirement was the same across the two RT conditions, but that the gain in the choice condition was obscured by the time required to program the deactivation component, then a rough estimate of the time to generate the deactivation instructions is 33.1 msec. (23.8 + 9.3).

Method

Apparatus: The apparatus was the same as in the previous experiments.

Subjects: Ten subjects were selected from the Cognitive Laboratory Subject Pool at the University of Oregon. Three subjects had participated in at least one of the first two experiments. All were right handed with normal or corrected to normal vision and hearing. The subjects were paid $6.

Procedure: The procedure was the same as in Experiment 1. However, only two different force ranges were tested. The maximal force trials required responses in which the response key was pressed with sufficient force to completely compress the springs (minimum force required was 13.9 N). Trials were counted as correct in the other force condition if a score on the arbitrary scale was between 40 (3.0 N) and 160 (12.0 N). This includes most of the possible range of the strain gauge. The subjects were not instructed to shoot for any particular force level in this latter condition, but rather were told to "feel free to use any force level which fell in this range". The digit 0 was matched to this condition and the digit 1 was used as the stimulus for the maximal responses. Absence of a second tone in the simple RT condition and the presence of the digit 4 in the choice RT condition were included for catch trials. Response latencies were again required to be below 600 msec. and response durations shorter than 400 msec.

Ten correct responses to each stimulus constituted a practice block and twenty similar responses were required in the test session. As before, the ordering of simple and choice RT conditions alternated. Half of the subjects started with a simple RT session whereas the other half began with a choice RT session. Unlike the earlier experiments, time permitted three test session of each RT condition. Hence, each subject produced 60 data points for analysis at each of the two force levels for both RT conditions.

Results

Table 3 presents the means and mean standard deviations for response latency, maximum force, response duration, and time to peak force. The latency data was entered into a 2 (RT Mode: Simple vs. Choice) X 2 (Target Force: 40-160 vs. Maximal) repeated measures ANOVA. As before, subjects were considerably faster in the simple RT condition, $F(1,9)=568.36$, $p<.001$. More important, the main effect of Target Force was also significant, $F(1,9)=7.79$, $p<.025$. Unexpectedly, the interaction of these two factors only approached significance, $F(1,9)=3.66$, $.05<p<.10$. The responses for the maximal press trials were faster in both the simple and choice RT conditions. However, the magnitude of the differences does support the model. The average gain in latency in the choice RT condition was 31.6 msec., whereas it was only 7.1 msec. in the simple RT condition. The latency difference of 31.6 msec. in the choice RT condition closely approximates the predicted value of 33.1 msec. (4)

Insert Table 3 about here

The error rates indicate that these tasks were considerably easier than in the previous experiments. The overall error rates were 14.5% and 8.7% in the choice and simple RT conditions, respectively. The number of responses which were out of the force range did not differ between the two target forces. This can be interpreted as validating our assumption that the inclusion of a wide force range did not impose any asymmetric accuracy demands. Indeed, the only large difference in errors between the two target forces was that more slow starts were recorded for the 40-160 condition in the choice RT paradigm. A similar reanalysis of the data as reported in Experiment 2 was performed with a latency maximum of 900 msec. This increased the mean gain in latency for the maximal force responses to 42.3 msec.

Discussion

Overall, the results of Experiment 3 support the programming model described above. The subjects were considerably faster in initiating responses under choice RT conditions when a signal to terminate force output was externally indicated upon reaching the maximal excursion of the strain gauge. The model postulates that, under such conditions, time can be saved in the response preparation phase by by-passing the deactivation component in the program constuction stage. Instead, deactivation occurs on-line when maximum force is externally signalled. A similar short cut can not be taken when the deactivation of force output must be internally controlled by the subject in that the deactivation component must be preprogrammed.

Contrary to our prediction, however, the interaction between RT mode and target force only approached significance. It is unclear why this interaction did not statistically surface. It may be that on a small percentage of the trials, subjects did not preprogram their responses and this contributed to the small differences in response latency in the simple RT condition. On the other hand, the assumption that force activation and deactivation are combined into a single component in the buffer ıy be incorrect (but see Footnote 3). The greater magnitude of ıe latency difference in the choice RT condition, however, ıpports the hypothesis that the time requirements of the ᵻactivation process are most evident in the program constuction tage.

Simple RT Condition:

Event:	Stimulus number on center of console	Warning tone	Auditory response signal	Response and feedback	Feedback termination
Time: (msec.)	0	2000	2750-3250		5000^{+}

Choice RT Condition:

Event:	Rest Period	Warning tone	Visual response signal	Response and feedback	Feedback termination
Time: (msec.)	0	2000	2750-3250		5000^{+}

Figure 1

Figure Captions

1. Sequence of events for the simple and choice RT conditions in all three experiments.

2. Model of the stages and subcomponents required to develop and implement a motor program for isometric contractions.

Simple RT Condition:

Force Range	Stimulus	Latency	Force	Response Duration	Time to Peak Force
40 - 160	0	248 (53)	86 (24)	184 (28)	78 (20)
Maximum (188)	1	241 (55)	188 (--)	282 (34)	71 (21)
Means		244	---	233	75

Choice RT Condition:

Force Range	Stimulus	Latency	Force	Response Duration	Time to Peak Force
40 - 160	0	441 (77)	84 (24)	191 (37)	81 (26)
Maximum (188)	1	410 (69)	188 (--)	290 (43)	75 (27)
Means		425	---	240	78

Table 3: Means and standard deviations for Experiment 3. Force measures are in terms of the arbitrary units of the A to D converter and the timing measures are in msec.

Simple RT Condition:

Time Range	Stimulus	Latency	Force	Response Duration
Ballistic (400)	0	289 (58)	99 (16)	243 (44)
700 - 1300	1	310 (63)	100 (12)	1035 (139)
1400 - 2600	2	316 (68)	100 (13)	1859 (321)
Means		305	100	----

Choice RT Condition:

Time Range	Stimulus	Latency	Force	Response Duration
Ballistic (400)	0	462 (73)	97 (14)	254 (51)
700 - 1300	1	451 (64)	101 (13)	1021 (142)
1400 - 2600	2	455 (67)	99 (12)	1883 (224)
Means		456	99	----

Table 2: Means and standard deviations for Experiment 2. Force measures are in terms of the arbitrary units of the A to D converter and the timing measures are in msec.

Simple RT Condition:

Force Range	Stimulus	Latency	Force	Response Duration	Time to Peak Force
40 - 80	0	283 (58)	62 (10)	174 (22)	72 (18)
80 - 120	1	282 (62)	100 (11)	206 (23)	88 (18)
120 - 160	2	291 (63)	138 (11)	242 (31)	109 (23)
Means		285	---	207	90

Choice RT Condition:

Force Range	Stimulus	Latency	Force	Response Duration	Time to Peak Force
40 - 80	0	476 (75)	60 (11)	170 (24)	67 (17)
80 - 120	1	458 (65)	100 (11)	218 (35)	91 (25)
120 - 160	2	454 (65)	138 (11)	254 (39)	114 (28)
Means		463	---	214	91

Table 1: Means and standard deviations for Experiment 1. Force measures are in terms of the arbitrary units of the A to D converter and the timing measures are in msec.

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a better estimate of the time required to program deactivation commands would be 24.5 msec. (Subtracting the 7.1 msec. difference obtained in the simple RT condition and thus, an estimate of the size of the artifact, from the 31.6 msec. difference in the choice RT condition.)

Footnotes

1. Throughout this paper, the term "movement" is applied to the isometric responses of the experiments. This may seem misleading since the actual movement is minimal (only the slight compression of the springs), but rather involves a change in muscle tension.

2. Due to a subsequent change in the calibration settings of the apparatus, the actual force values are unavailable.

3. A similar reanalysis of the data from Experiment 1 showed, that while the latencies were inflated, the differences between the different force levels remained unchanged.

4. The 7.1 msec. gain in the simple RT condition may be an artifact of our measurement method. The time to peak force is approximately the same for both target forces. Thus, the velocity (and acceleration) must be greater for maximal responses since a larger force is generated in the same amount of time. This implies that the time from which the subject actually began to press to when he actually reaches the criterion point at which response initiation is recorded, is less for the maximal responses. Data produced by the experimenter indicate that the size of the artifact is between 4 and 8 msec. This same artifact may explain why in three of the four RT conditions of Experiment 1 and the supplementary experiment, subjects were slightly faster on the large force trials in comparison to the samll target force. It should be noted that this artifact would also have inflated the difference in mean latency in the choice RT condition of Experiment 3. If this artifact is actually present,

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magnitude. However, the antagonist activity also disappeared when subjects were instructed to either passively relax their finger after responding or to maintain the response for one second. The parallel between this last condition and Experiment 2 is obvious. A design similar to Experiment 3 was used by Waters and Strick (1981) who found that the antagonist burst was considerably reduced and even abolished when ballistic responses were terminated by a mechanical stop (see also Marsden, Obeso, and Rothwell, 1983). Other researchers (Conrad and Brooks, 1974; Vilas and Hore, 1981) have found that cerebellar cooling in primates primarily disrupts the activity of the antagonist muscles. After cooling, the antagonist is generally evident only after a mechanical stop is contacted, rather than before contact as is found with normal primate subjects. Thus, the antagonist activity appears to have switched from a braking mechanism to a feedback response.

It would be premature to conclude that the deactivation component of the motor programming model postulated in this paper directly corresponds to the subsequent activity of the antagonist muscle. However, the finding that a change in response strategy leads to significant changes in both response programming and response execution is promising. A study which will examine both measures concurrently is presently being planned.

parameters of force and timing provides only indirect evidence for the hypothesis that the two variables are independently controlled. More direct support would require a comparison between conditions in which both of these factors may vary. However, data collected during the execution of movement has generally supported the notion that force and timing are independently controlled (e.g Freund, 1983; Ghez, 1979). It would seem most parsimonious that the preparatory processes would mirror this independence.

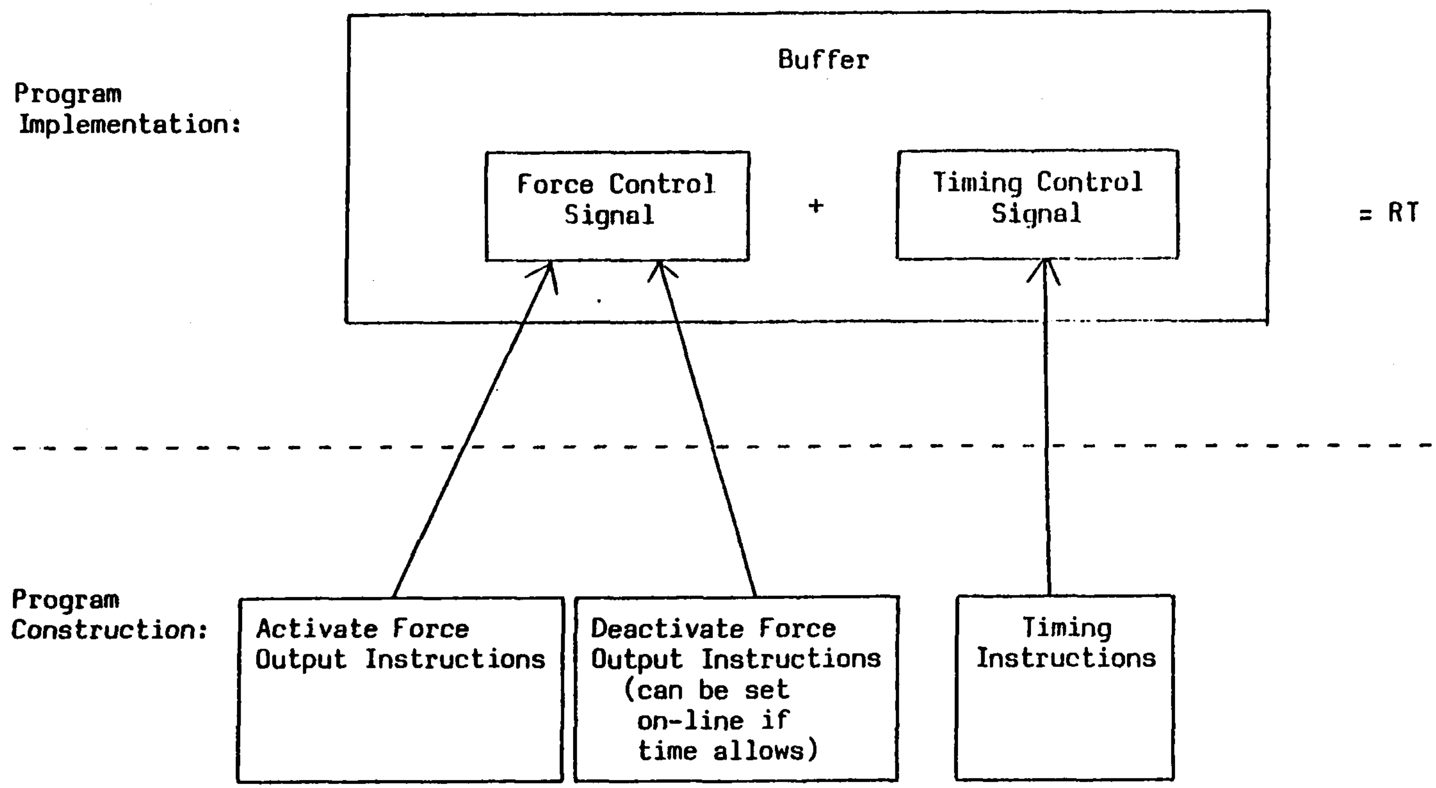
Perhaps the most suprising aspect of the data reported here is the finding that all ballistic responses can not be treated as an homogenous group in terms of the processing demands they entail. Ballistic responses in which the subject must control the deactivation of force output involve a more complex motor program than similar responses in which a signal to terminate force output is externally provided. While it has been widely suggested that different control strategies are involved in ballistic and ramped movements (e.g. Hallett, Shahani, and Young, 1975; Brown and Cooke, 1981), the hypothesis that subjects can employ different control strategies for ballistic responses has only recently been advanced. Most of this research has been designed to test the conjecture that the antagonist component of the biphasic and triphasic bursts typically seen in EMG recordings during ballistic responses, serves as a braking mechanism. Meinck et al, (1984) observed this triphasic activity in rapid isotonic movements and found that only the second agonist burst was eliminated in isometric movements of similar

General Discussion

The experiments reported in this paper represent an attempt to explain why response latency increases as a motor program becomes more complex. The basic premise underlying this investigation is that the best approach for developing a definition of "complexity" requires a thorough description of how complexity is manifested in the simplest movements. Research which is designed to look at the components of more involved motor programs will only be fruitful when the basic foundation has been developed.

The results indicate that program complexity does not vary as a function of the force required in an isometric contraction. The time required to select and generate a desired output level of force is invariant across the range of forces examined. The parameterization of timing, however, is a function of the real-time demands of the movement. The present study suggests that the discrete presence or absence of timing is one parameter. In addition, if timing is necessary, then its programming time may depend on the length of time as suggested by Klapp and Erwin (1976) and hinted at by the non-significant RT difference in Experiment 2 between the 1 sec. and 2 sec. response duration movements. As Klapp and Erwin (1976) have argued, control of longer movements may involve longer neural circuits in order to provide the required time delays between the components of the response.

This asymmetry in the processing demands for setting the



Buffer
Program
Implementation:
Force Control
Signal
+
Timing Control
Signal
= RT
Program
Construction:
Activate Force
Output Instructions
Deactivate Force
Output Instructions
(can be set
on-line if
time allows)
Timing
Instructions

Figure 2

END

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